

Buffer-Aided Relay Selection Algorithms for Physical-Layer Security in Wireless Networks

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Abstract—In this work, we consider the use of buffer-aided relays, linear precoding techniques and multiple antennas for physical-layer security in wireless networks. We develop relay selection algorithms to improve the secrecy-rate performance of cooperative multi-user multiple-antenna wireless networks. In particular, we propose a novel finite buffer-aided relay selection algorithm that employs the maximum likelihood (ML) criterion to select sets of relays which fully exploit the flexibility offered by relay nodes equipped with buffers. Numerical results show the benefits of the proposed techniques as compared to prior art.

Index Terms—physical-layer security, cooperative relaying, relay selection.

I. INTRODUCTION

In wireless networks, security is always an aspect of fundamental importance. Early work suggested the idea of generating keys to ensure the transmission security [1]. The keys generated by these algorithms implemented in the network layer are nearly unbreakable, but the complexity is an obvious drawback. Recently, physical-layer security has been advocated as a promising alternative which can ensure the transmission security with much lower computational complexity and delay.

Relaying techniques for physical-layer security in wireless networks have attracted significant research interest in the last few years due to their ability to improve the level of secrecy in the system [2], [3]. In a typical link-level setup, a group of relays are used to help the communications between source and destination [4]. The most reliable relay can be chosen to transmit the signal [5], [6], [7]. Based on this idea, different relay selection policies can be employed according to different scenarios and requirements. According to [8], max-min relay selection is considered as the optimal selection scheme for conventional decode-and-forward (DF) relay setups. The work in [8] introduced max-link relay selection schemes [9]–[11] which relax the limitation that the source and relay transmission must be fixed, and allow each slot to be allocated dynamically to the source or a relay transmission. In [8] and [12] a max-max relay selection has been studied with a single destination, where a cooperative network with buffers of finite size at the relay nodes is considered. The use of a buffer-aided relay system for improving the physical-layer security has been considered in [13], where a max-ratio relay selection is

proposed based on the best channel ratio of the legitimate links to the eavesdroppers. In [14], a two-hop buffer-aided relay selection has been introduced for physical-layer security. In the presence of an arbitrary number of users, linear precoding techniques [15] can be employed to assist the buffer-aided relay systems [16]–[17] and improve their secrecy rate.

In this work, we propose novel relay selection strategies for physical-layer security in buffer-aided multiuser multiple-antenna relay networks [18]. The first proposed buffer-aided maximum-likelihood (ML) relay selection (ML-RS) algorithm employs the ML criterion for relay selection. In each slot, the relay with the best performance is selected to receive or forward signals. In the presence of multiple relays, different sets of relay combinations can be employed to further enhance the performance of the network. Therefore, we also present a technique to select a set of relays based on the ML criterion which is denoted ML-SRS algorithm. The proposed relay selection algorithms are compared with existing techniques via computer simulations.

This paper is organized as follows. Section II details the system model, describes the use of the amplify-and-forward (AF) relaying protocol in the chosen system, and states the problem of physical-layer security. Section III presents the proposed ML-type relay selection algorithm, whereas Section IV details the proposed ML-type algorithm for selecting sets of relays. Section V shows and discusses then numerical results, while the conclusions are drawn in Section VI.

II. SYSTEM MODEL AND PHYSICAL-LAYER SECURITY

In this section, the system model encompassing a buffer-aided multiuser multiple-antenna relay network is described along with the use of the AF relaying protocol and the problem of physical-layer security in such a system is formulated.

A. System Model

We consider a multiuser multiple-input multiple-output (MIMO) system with one source S equipped with N_t antennas, N_D users each with N_r antennas at the Destination D , a cluster ζ with M amplify-and-forward (AF) relays as well as N_E eavesdroppers each with N_e antennas. All nodes are characterized by the half-duplex constraint and each relay R_m has a buffer Q_m with finite size T equipped with N_m antennas. The condition $0 \leq \varphi(Q_m) \leq T$ gives the number of data symbols stored in the buffer Q_m . With a feedback channel the selected relay nodes can be informed for further

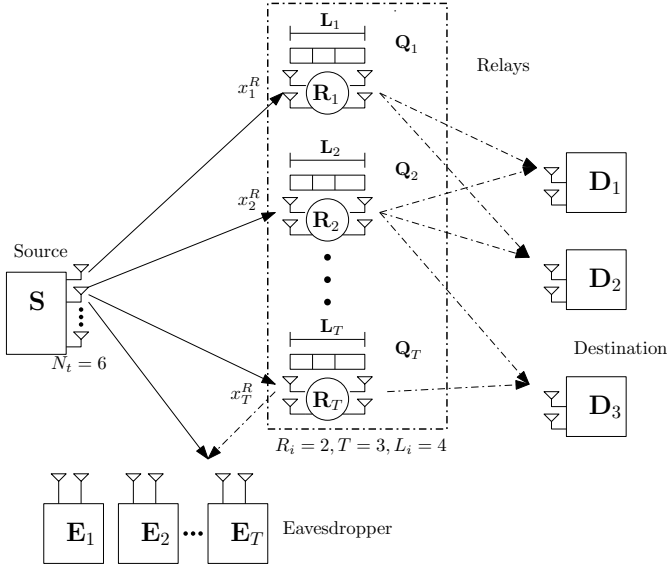


Fig. 1: Buffer-aided multiuser MIMO system.

transmission. Moreover, in order to apply linear precoding techniques there are two assumptions. One is that the number of transmit antennas is larger than the sum of the receive antennas. Another is that the channels are static over a packet of N_t symbols. The operation of the system can be divided into two transmission phases.

In Phase I ($S \rightarrow R$), the source transmits the signal to the relays. The transmit signal to the m th relay node $\mathbf{x}_{sr_m} \in \mathbb{C}^{N_m \times 1}$ with linear precoding techniques is given by

$$\mathbf{x}_{sr_m} = \mathbf{P}_{sr_m} \mathbf{s}_{sr_m}, \quad (1)$$

where $\mathbf{s}_{sr_m} \in \mathbb{C}^{N_m \times 1}$ is a vector with the transmitted symbols and $\mathbf{P}_{sr_m} \in \mathbb{C}^{N_t \times N_m}$ is the precoding matrix. Considering a linear zero-forcing precoding technique [15], the precoding matrix for the m th relay node can be generated by

$$\mathbf{P}_{sr_m} = \mathbf{H}_{sr_m}^H (\mathbf{H}_{sr_m} \mathbf{H}_{sr_m}^H)^{-1}, \quad (2)$$

where $\mathbf{H}_{sr_m} \in \mathbb{C}^{N_m \times N_t}$ is the channel between the source to the m th relay. The received signal at the m th relay node can be expressed as

$$\mathbf{y}_{sr_m} = \alpha_{sr_m} \beta_{sr_m} \mathbf{H}_{sr_m} \mathbf{x}_{sr} + \mathbf{n}_{sr_m}, \quad (3)$$

where α_{sr} is the power path loss, β_{sr} is the log-normal shadowing (LNS) fading channel loss and $\mathbf{n}_{sr_m} \in \mathbb{C}^{N_m \times 1}$ is the Gaussian noise between the source and the relay which follows the distribution $\mathcal{CN}(0, \sigma_{n_{sr}}^2)$. According to [19], α_{sr} is known as the distance based fading (or path loss). It is a representation of how a signal is attenuated the further it travels in the medium the system operates within. An exponential based path loss model can be described by

$$\alpha = \frac{\sqrt{L}}{\sqrt{d}^\rho} \quad (4)$$

where L is the known path loss associated with D , d is the distance of interest relative to D and ρ is the path loss exponent, which is typically set between 2 and 5. The parameter β_{sr} refers to the shadow fading which can be

described using the log-normal probability distribution given by

$$\beta = 10^{(\frac{\sigma_s \mathcal{CN}(0,1)}{10})} \quad (5)$$

where σ_s is the shadowing spread in dB which is typically given between 0 and 9dB [20]. Both α_{sr} and β_{sr} are used to describe the position of the relay.

B. Amplify-and-Forward (AF) Relaying Protocol

In Phase II ($R \rightarrow D$), the relays transmit signals to the destination with the AF relaying protocol. Each relay will transmit a weighted version of the noisy signal that they received during Phase I. Let the transmitted signal of all relays be denoted by the product $\text{diag}\{\mathbf{w}\} \mathbf{y}_{sr}$. To simplify the description of the system, we assume that each relay node and user has the same number of antennas $N_m = N_r$ and the weight at each relay node $\text{diag}\{\mathbf{w}\} = \mathbf{I}$. Then the received signal at the destination for the r th user $\mathbf{y}_{dr} \in \mathbb{C}^{N_r \times 1}$ can be expressed as

$$\mathbf{y}_{dr} = \alpha_{dr} \beta_{dr} \mathbf{H}_{dr} \mathbf{P}_{dr} \mathbf{y}_{sr_m} + \mathbf{n}_{dr}, \quad (6)$$

where $\mathbf{H}_{dr} \in \mathbb{C}^{N_r \times (M \times N_m)}$ and $\mathbf{P}_{dr} \in \mathbb{C}^{(M \times N_m) \times N_r}$ are the channel and the precoding matrices [?], [21]–[24] from the relays to the destination, where advanced estimation [25]–[29] and detection [?], [30]–[34] algorithms can be used. The vector $\mathbf{n}_{dr} \in \mathbb{C}^{N_r \times 1}$ represents the Gaussian noise at the destination.

C. Physical-Layer Security

According to information theory, the level of secrecy is measured by the uncertainty of Eve about the message R_e which is called the equivocation rate. The secrecy capacity C_s is the supremum of all achievable secrecy rates.

The MIMO system secrecy capacity can be expressed as:

$$C_s = \max_{\mathbf{Q}_s \geq 0, \text{Tr}(\mathbf{Q}_s) = E_s} \log(\det(\mathbf{I} + \mathbf{H}_{ba} \mathbf{Q}_s \mathbf{H}_{ba}^H)) - \log(\det(\mathbf{I} + \mathbf{H}_{ea} \mathbf{Q}_s \mathbf{H}_{ea}^H)), \quad (7)$$

In (7) \mathbf{Q}_s is the covariance matrix associated with the signal after precoding, whereas \mathbf{H}_{ba} , \mathbf{H}_{ea} represent the channel from source a to user b , eavesdropper e , respectively. Then based on (8), the capacity from the source to the relay can be expressed as:

$$C_{sr} = \log(\det(\mathbf{I} + \mathbf{H}_{sr} \mathbf{Q}_s \mathbf{H}_{sr}^H)). \quad (8)$$

Similarly, the capacity to the eavesdropper is given by

$$C_{se} = \log(\det(\mathbf{I} + \mathbf{H}_{se} \mathbf{Q}_s \mathbf{H}_{se}^H)) \quad (9)$$

And according to (6), the rate at the destination can be expressed as:

$$R_d = \frac{1}{2} \log(\det(\mathbf{I} + \frac{\mathbf{H}_{rd} \mathbf{P}_d \mathbf{H}_{sr} \mathbf{Q}_s \mathbf{H}_{sr}^H \mathbf{P}_d^H \mathbf{H}_{rd}^H}{\mathbf{H}_{rd} \mathbf{Q}_s \mathbf{H}_{rd}^H + \mathbf{I}})), \quad (10)$$

where the scalar factor 1/2 is due to the fact that two time units are required in two phases. Similarly, the rate at the eavesdropper is given by

$$R_e = \frac{1}{2} \log(\det(\mathbf{I} + \frac{\mathbf{H}_{re} \mathbf{P}_d \mathbf{H}_{sr} \mathbf{Q}_s \mathbf{H}_{sr}^H \mathbf{P}_d^H \mathbf{H}_{re}^H}{\mathbf{H}_{re} \mathbf{Q}_s \mathbf{H}_{re}^H + \mathbf{I}})) \quad (11)$$

where $\Gamma = \mathbf{I} + \mathbf{H}_{se}\mathbf{Q}_s\mathbf{H}_{se}^H$. Then the overall buffer-aided relay system secrecy rate is given by,

$$\begin{aligned} R &= R_d - R_e \\ &= \frac{1}{2} \log(\det(\mathbf{I} + \frac{\mathbf{H}_{rd}\mathbf{P}_d\mathbf{H}_{sr}\mathbf{Q}_s\mathbf{H}_{sr}^H\mathbf{P}_d^H\mathbf{H}_{rd}^H}{\mathbf{H}_{rd}\mathbf{Q}_s\mathbf{H}_{rd}^H + \mathbf{I}})) \\ &\quad - \frac{1}{2} \log(\det(\Gamma + \frac{\mathbf{H}_{re}\mathbf{P}_d\mathbf{H}_{sr}\mathbf{Q}_s\mathbf{H}_{sr}^H\mathbf{P}_d^H\mathbf{H}_{re}^H}{\mathbf{H}_{re}\mathbf{Q}_s\mathbf{H}_{re}^H + \mathbf{I}})) \end{aligned} \quad (12)$$

Then the secrecy rate for each pair of user and relay can be calculated with a similar formula.

III. PROPOSED BUFFER-AIDED ML CRITERION BASED RELAY SELECTION (ML-RS) ALGORITHM

According to [19], to approach the channel capacity, the maximum likelihood (ML) decoder can be applied at the receiver to obtain the following estimate of the transmitted data symbols:

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \in \Phi} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2, \quad (13)$$

With a cooperative relay system, to achieve as high transmission rate as possible, the maximum likelihood (ML) criterion can be used to select the best relay for transmission which can be expressed as:

$$\hat{\mathbf{H}} = \arg \min_{\mathbf{H} \in \chi} \|\mathbf{y} - \alpha\beta\mathbf{H}\mathbf{x}\|^2, \quad (14)$$

where χ represents the set of all possible combinations of links \mathbf{H} . For example, if there are 3 relays in the relay pool. The total number of possible link combinations would be 3. If the total channel \mathbf{H} is formed as $\mathbf{H} = [\mathbf{H}_1 \ \mathbf{H}_2 \ \mathbf{H}_3]$. Then the possible selection would be \mathbf{H}_1 , \mathbf{H}_2 or \mathbf{H}_3 . In this proposed algorithm, we use the ML criterion as the relay selection criterion, then combine the ML relay selection strategy with the buffer. The selection procedure can be described by

$$\mathbf{R}^k = \arg \min_{\mathbf{R}_m \in \zeta} \left\{ \bigcup_{\mathbf{R}_p \in \zeta: \varphi(Q_p) \neq T} \hat{\mathbf{H}}_{S, \mathbf{R}_p}, \bigcup_{\mathbf{R}_q \in \zeta: \varphi(Q_q) \neq 0} \hat{\mathbf{H}}_{\mathbf{R}_q, D} \right\} \quad (15)$$

where $\bigcup_{\mathbf{R}_p \in \zeta: \varphi(Q_p) \neq T} \hat{\mathbf{H}}_{S, \mathbf{R}_p}$ are the channel combinations with the smallest Euclidean distance according to Eq.(14) at the relay. The parameter $\bigcup_{\mathbf{R}_q \in \zeta: \varphi(Q_q) \neq 0} \hat{\mathbf{H}}_{\mathbf{R}_q, D}$ refers to the channel combinations related to the destination. In Eq.(15), the first aspect shown is that if the buffer is full ($\varphi(Q_m) = T$) the relay can only transmit signals and if the buffer is empty ($\varphi(Q_m) = 0$) the relay can only receive signals. Secondly, as the relay selection policy is combined with the buffer, the buffer-aided relay can achieve better channel selection over time. With the ML relay selection (ML-RS) strategy illustrated in (15), the main steps of the proposed Buffer-Aided ML-RS algorithm are shown in Algorithm 1.

IV. PROPOSED BUFFER-AIDED ML CRITERION WITH SET OF RELAYS SELECTION (ML-SRS) ALGORITHM

In the presence of an arbitrary number of relays, one can consider the selection of a set of relays rather than the best relay. The selection criterion has the same equation as Eq.(14). We also take three relays as an example, then the total number

Algorithm 1 Buffer-Aided ML-RS Algorithm

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loop
   $\varphi(Q_m) = 0$ 
  for  $m = 1 : M$  do
     $\hat{\mathbf{H}}_{S, \mathbf{R}_m} = \arg \min_{\mathbf{R}_m \in \zeta} \|\mathbf{y}_{\text{sr}_m} - \alpha_{\text{sr}_m} \beta_{\text{sr}_m} \mathbf{H}_{\text{sr}_m} \mathbf{x}_{\text{sr}_m}\|^2$ 
  end for
  for  $d = M + 1 : M + N_D$  do
     $\hat{\mathbf{H}}_{\mathbf{R}_d, D} = \arg \min_{\mathbf{R}_d \in \zeta} \|\mathbf{y}_{\text{dr}} - \alpha_{\text{dr}} \beta_{\text{dr}} \mathbf{H}_{\text{dr}} \mathbf{y}_{\text{sr}(d-M)}\|^2$ 
  end for
   $\mathbf{R}^k = \arg \min_{\mathbf{R}_k \in \zeta} \{ \bigcup_{\mathbf{R}_m \in \zeta: \varphi(Q_m) \neq T} \hat{\mathbf{H}}_{S, \mathbf{R}_m}, \bigcup_{\mathbf{R}_d \in \zeta: \varphi(Q_d) \neq 0} \hat{\mathbf{H}}_{\mathbf{R}_d, D} \}$ 
  if  $k \leq M$  &  $\varphi(Q_k) \neq T$  then
     $Q_k = y_{\text{sr}}$ 
     $\varphi(Q_k) = \varphi(Q_k) + N_m$ 
  else
    if  $k > M$  &  $\varphi(Q_k) \neq 0$  then
       $y_{\text{sr}(d-M)} = Q_k$ 
       $\varphi(Q_k) = \varphi(Q_k) - N_m$ 
    end if
  end if
end loop

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of possible combinations of links would be 7. If the total channel \mathbf{H} is formed as $\mathbf{H} = [\mathbf{H}_1 \ \mathbf{H}_2 \ \mathbf{H}_3]$. Then the possible selection would be \mathbf{H}_1 , \mathbf{H}_2 , \mathbf{H}_3 , $[\mathbf{H}_1 \ \mathbf{H}_2]$, $[\mathbf{H}_1 \ \mathbf{H}_3]$, $[\mathbf{H}_2 \ \mathbf{H}_3]$ and $[\mathbf{H}_1 \ \mathbf{H}_2 \ \mathbf{H}_3]$. Based on Eq.(15), in Phase II the selection of the set of relays is achieved with the aid of a feedback channel from the destination to the relays. A sequence of bits can be used to indicate whether the relays are switched on or off. The proposed selection of the set of relays denoted ML-SRS algorithm can be expressed as

$$\mathbf{R}^K = \arg \min_{\mathbf{R}_M \in \zeta} \left\{ \bigcup_{\mathbf{R}_M \in \zeta: \varphi(Q_M) \neq T} \hat{\mathbf{H}}_{S, \mathbf{R}_M}, \bigcup_{\mathbf{R}_N \in \zeta: \varphi(Q_N) \neq 0} \hat{\mathbf{H}}_{\mathbf{R}_N, D} \right\} \quad (16)$$

where K, M, N are subsets of ζ . The major difference between Eq.(16) and Eq.(15) is that, due to the increased number of relays, different relays can be selected for transmission which is known as sets of relays selection (SRS). The set $\bigcup_{\mathbf{R}_M \in \zeta: \varphi(Q_M) \neq T} \hat{\mathbf{H}}_{S, \mathbf{R}_M}$ indicates that the channel combinations give the smallest Euclidean distance with respect to an M set of relays selection from the source to the relays. The set $\bigcup_{\mathbf{R}_N \in \zeta: \varphi(Q_N) \neq 0} \hat{\mathbf{H}}_{\mathbf{R}_N, D}$ has the same definition with an N set of relays links to the destination. Compared to the single relay selection, SRS gives more flexible selections at the relays, which contributes to the improvement of the secrecy performance. The main steps are given in Algorithm 2.

V. SIMULATION RESULTS

In the simulation of a single-antenna scenario, we assume that the weight at each relay node is given by $\text{diag}\{\mathbf{w}\} = \mathbf{I}$. The transmitter is equipped with $N_t = 3$ antennas and each relay node is equipped with one antenna for receiving or transmitting data. Each user is equipped with a single antenna and the number of users is set to $N_D = 3$. At the same time $N_E = 3$ eavesdroppers are receiving data from the source. In

Algorithm 2 Buffer-Aided ML-SRS Algorithm

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for  $d = M + 1 : M + N_D$  do
   $\hat{H}_{dR_M,D}$ 
   $= \arg \min_{H_{\hat{M}d} \in \chi} \|y_{\hat{M}d} - \alpha_{\hat{M}d} \beta_{\hat{M}d} H_{\hat{M}d} x_{\hat{M}d}\|^2$ 
end for
 $R^K = \arg \min_{R_M \in \zeta} \{ \bigcup_{R_M \in \zeta: \varphi(Q_M) \neq T} \hat{H}_{S,R_M}, \bigcup_{R_N \in \zeta: \varphi(Q_N) \neq 0} \hat{H}_{R_N,D} \}$ 

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the simulation of the multiuser MIMO scenario, the transmitter is equipped with $N_t = 6$ antennas and each relay node is equipped with $N_m = 2$ antennas for receiving or transmitting. Each user is equipped with $N_r = 2$ antennas and the number of users is set to $N_D = 3$. At the same time $N_E = 3$ eavesdroppers are all equipped with $N_e = 2$ antennas. In both scenarios, a zero-forcing precoding technique is implemented at the transmitter and at the relays, and the secrecy rate is calculated with Eq.(12).

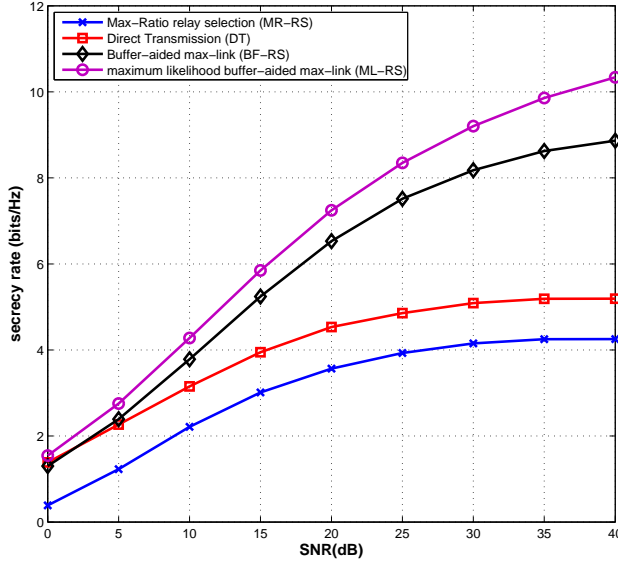


Fig. 2: Multi-user system with a single-antenna scenario and the simulation parameters $N_t = 3, N_m = 1, N_r = 1, N_e = 1$ and $M = 3, N_D = 3, N_E = 3, T = 3$

The simulation results shown in Fig. 2 indicate that the proposed Buffer-Aided ML-RS algorithm outperforms the conventional relay selection strategy with and without buffers. With the weight at each relay node set to $\text{diag}\{w\} = I$, the Max-Ratio relay selection is worse than Direct Transmission, as the noise is enhanced by the AF relays. Compared with the Direct Transmission, the buffer-aided max-link selection policy selects the link with the best performance using the relays equipped with buffers. In particular, the proposed Buffer-Aided ML-RS algorithm contributes to the improvement of the users channel capacity so the secrecy rate will also have an improvement.

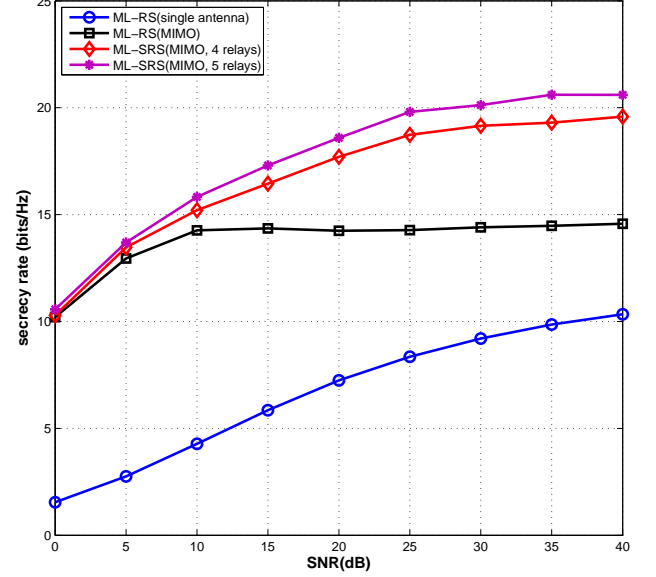


Fig. 3: Secrecy rate with the ML-SRS strategy for MU-MIMO systems with $N_t = 6, N_m = 2, N_r = 2, N_e = 2$ and $M = 3, N_D = 3, N_E = 3, T = 6$

In Fig. 3, we consider a MIMO system scenario in which the proposed algorithms have better secrecy rate performance than the single-antenna configuration. In low SNRs, the secrecy rate of the proposed ML-RS algorithm with the MIMO scenario is around 8 – 9 bits/Hz better than the single-antenna system. Then the gap between the two scenario becomes narrower with the increase of the SNR. Moreover, in the simulation the proposed Buffer-Aided ML-SRS algorithm with different numbers of relays is compared with the proposed Buffer-Aided ML-RS algorithm in the MIMO scenario considered. When we compare the performance of the system with 4 relays selected with that of the system with 3 relays, the secrecy rate is improved significantly. In a scenario with 5 relays, the improvement is not as significant as before.

VI. CONCLUSION

In this work, we have considered the use of buffer-aided relays, linear precoding techniques and MIMO for physical-layer security in wireless networks. We have developed relay selection algorithms to improve the secrecy-rate performance of cooperative multi-user multiple-antenna wireless networks. In particular, we have presented a novel finite buffer-aided relay selection algorithm that employs the ML criterion to select sets of relays which fully exploit the flexibility offered by relay nodes equipped with buffers. Numerical results have shown that the proposed techniques can offer significant gains in terms of secrecy rate as compared to existing algorithms.

REFERENCES

- [1] S.Soni, H. Agrawal, and M. Sharma, "Analysis and comparison between aes and des cryptographic algorithm," *International Journal of Engineering and Innovative Technology (IJEIT)*, vol. 2, no. 3, December 2012.

- [2] L. Dong, Z. Han, A. Petropulu, and H.V.Poor, "Improving wireless physical layer security via cooperating relays," *IEEE Transactions on Signal Processing*, vol. 58, no. 3, pp. 1875–1888, February 2010.
- [3] H. Wang, M. Luo, X. Xia, and Q. Yin, "Joint cooperative beamforming and jamming to secure af relay systems with individual power constraint and no eavesdropper's csi," *IEEE Signal Processing Letters*, vol. 20, no. 1, pp. 39–42, November 2012.
- [4] R. C. de Lamare and A. Alcaim, "Strategies to improve the performance of very low bit rate speech coders and application to a variable rate 1.2 kb/s codec," *IEE Proceedings Vision, Image and Signal Processing*, vol. 152, no. 1, pp. 74–86, Feb 2005.
- [5] T. Wang, R. C. de Lamare, and P. D. Mitchell, "Low-complexity set-membership channel estimation for cooperative wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 6, pp. 2594–2607, July 2011.
- [6] Y. Cai, R. C. de Lamare, and R. Fa, "Switched interleaving techniques with limited feedback for interference mitigation in ds-cdma systems," *IEEE Transactions on Communications*, vol. 59, no. 7, pp. 1946–1956, July 2011.
- [7] T. Peng, R. C. de Lamare, and A. Schmeink, "Adaptive distributed space-time coding based on adjustable code matrices for cooperative mimo relaying systems," *IEEE Transactions on Communications*, vol. 61, no. 7, pp. 2692–2703, July 2013.
- [8] I. Krikidis, T. Charalambous, and J. S. Thompson, "Buffer-aided relay selection for cooperative diversity systems without delay constraints," *IEEE Transactions on Wireless Communications*, vol. 11, no. 5, pp. 1957–1967, May 2012.
- [9] P. Clarke and R. C. de Lamare, "Transmit diversity and relay selection algorithms for multirelay cooperative mimo systems," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 3, pp. 1084–1098, March 2012.
- [10] R. C. de Lamare, "Joint iterative power allocation and linear interference suppression algorithms for cooperative ds-cdma networks," *IET Communications*, vol. 6, no. 13, pp. 1930–1942, Sept 2012.
- [11] T. Wang, R. C. de Lamare, and A. Schmeink, "Joint linear receiver design and power allocation using alternating optimization algorithms for wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 9, pp. 4129–4141, Nov 2012.
- [12] A. Ikhlef, D. S. Michalopoulos, and R. Schober, "Max-max relay selection for relays with buffers," *IEEE Transactions on Wireless Communications*, vol. 11, no. 3, pp. 1124–1135, March 2012.
- [13] G. Chen, Z. Tian, Y. Gong, Z. Chen, and J. A. Chambers, "Max-ratio relay selection in secure buffer-aided cooperative wireless networks," *IEEE Transactions on Information Forensics and Security*, vol. 9, no. 4, pp. 719–729, April 2014.
- [14] J. Huang and A. L. Swindlehurst, "Buffer-aided relaying for two-hop secure communication," *IEEE Transactions on Wireless Communications*, p. DOI:10.1109/TWC.2014.2334602, July 2014.
- [15] G. Geraci, M. Egan, J. Yuan, A. Razi, and I. B. Collings, "Secrecy sum-rates for multi-user mimo regularized channel inversion precoding," *IEEE Transactions on Communications*, vol. 60, no. 11, pp. 3472–3482, November 2012.
- [16] H. Liu, P. Popovski, E. de Carvalho, and Y. Zhao, "Sum-rate optimization in a two-way relay network with buffering," *IEEE Communications Letters*, vol. 17, no. 1, pp. 95–98, January 2013.
- [17] N. Zlatanov and R. Schober, "Buffer-aided relaying with adaptive link selection: Fixed and mixed rate transmission," *IEEE Transactions on Information Theory*, vol. 59, no. 5, pp. 2816–2840, May 2013.
- [18] R. C. de Lamare, "Massive mimo systems: Signal processing challenges and future trends," *URSI Radio Science Bulletin*, December 2013.
- [19] T. Hesketh, P. Clarke, R. C. de Lamare, and S. Wales, "Joint maximum likelihood detection and power allocation in cooperative mimo relay systems," *2012 International ITG Workshop on Smart Antennas (WSA)*, pp. 325–331, March 2012.
- [20] T. Hesketh, R. C. de Lamare, and S. Wales, "Joint maximum likelihood detection and link selection for cooperative mimo relay systems," *IET Communications*, vol. 8, no. 14, pp. 2489–2499, September 2014.
- [21] K. Zu and R. C. de Lamare, "Low-complexity lattice reduction-aided regularized block diagonalization for mu-mimo systems," *IEEE Communications Letters*, vol. 16, no. 6, pp. 925–928, June 2012.
- [22] K. Zu, R. C. de Lamare, and M. Haardt, "Multi-branch tomelinson-harashima precoding for single-user mimo systems," in *Smart Antennas (WSA), 2012 International ITG Workshop on*, March 2012, pp. 36–40.
- [23] —, "Multi-branch tomelinson-harashima precoding design for mu-mimo systems: Theory and algorithms," *IEEE Transactions on Communications*, vol. 62, no. 3, pp. 939–951, March 2014.
- [24] L. Zhang, Y. Cai, R. C. de Lamare, and M. Zhao, "Robust multibranch tomelinson harashima precoding design in amplify-and-forward mimo relay systems," *IEEE Transactions on Communications*, vol. 62, no. 10, pp. 3476–3490, Oct 2014.
- [25] R. C. de Lamare and R. Sampaio-Neto, "Adaptive reduced-rank equalization algorithms based on alternating optimization design techniques for mimo systems," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 6, pp. 2482–2494, July 2011.
- [26] —, "Reduced-rank space-time adaptive interference suppression with joint iterative least squares algorithms for spread-spectrum systems," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 3, pp. 1217–1228, March 2010.
- [27] —, "Adaptive reduced-rank processing based on joint and iterative interpolation, decimation, and filtering," *IEEE Transactions on Signal Processing*, vol. 57, no. 7, pp. 2503–2514, July 2009.
- [28] Y. Cai and R. C. de Lamare, "Adaptive linear minimum ber reduced-rank interference suppression algorithms based on joint and iterative optimization of filters," *IEEE Communications Letters*, vol. 17, no. 4, pp. 633–636, April 2013.
- [29] H. Ruan and R. C. de Lamare, "Robust adaptive beamforming using a low-complexity shrinkage-based mismatch estimation algorithm," *IEEE Signal Processing Letters*, vol. 21, no. 1, pp. 60–64, Jan 2014.
- [30] R. de Lamare, R. Sampaio-Neto, and A. Hjørungnes, "Joint iterative interference cancellation and parameter estimation for cdma systems," *IEEE Communications Letters*, vol. 11, no. 12, pp. 916–918, December 2007.
- [31] Y. Cai and R. C. de Lamare, "Space-time adaptive mmse multiuser decision feedback detectors with multiple-feedback interference cancellation for cdma systems," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, pp. 4129–4140, Oct 2009.
- [32] P. Li and R. C. de Lamare, "Adaptive decision-feedback detection with constellation constraints for mimo systems," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 2, pp. 853–859, Feb 2012.
- [33] R. C. de Lamare, "Adaptive and iterative multi-branch mmse decision feedback detection algorithms for multi-antenna systems," *IEEE Transactions on Wireless Communications*, vol. 12, no. 10, pp. 5294–5308, October 2013.
- [34] P. Li and R. C. de Lamare, "Distributed iterative detection with reduced message passing for networked mimo cellular systems," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 6, pp. 2947–2954, July 2014.